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Secular Climatic Fluctuations In Southwestern Colorado

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ABSTRACT—Precipitation and temperature data since records began in southwestern Colorado are analyzed on a seasonal basis. Interstation correlations for recent years indicate that the region responds fairly uniformly to seasonal variations in precipitation, but this was not true earlier this century when precipitation variability was higher. Changes in the dependence of precipitation on elevation are also shown. Annual precipitation totals were low about 1860, 1900, 1930-35 and 1950-55. Mean annual temperatures appear to have fallen from about 1867 to about 1930 when the trend reversed. Overall, the climate of southwestern Colorado in the 1860s appears to have been warmer and at least as dry as current normals.

1. INTRODUCTION

Studies of secular climatic fluctuations in the United States have been restricted primarily to the eastern and midwestern states (Mitchell 1961, Wahl 1968, Baker 1960, Ludlum 1966, 1968, Landsberg 1949, Conover 1951). This, of course, reflects the longer instrumental records available for the eastern half of the continent. Fewer studies have been carried out for Western States. Roden (1966) analyzed the longest temperature records for Pacific coastal stations, where some observations have been kept since 1821. Roden's study indicated that no secular temperature changes have occurred in nonurban environments over the past century, whereas temperatures in large cities have increased substantially. Wahl and Lawson (1970) used areal averages for unspecified stations to estimate differences between the climate of the 1850s and 1860s and that of the period 1931-60. Their analysis indicates that "a distinctly warmer and decisively wetter" climate prevailed in the western United States during the midnineteenth century.

On a smaller scale, Sellers (1960) and Von Eschen (1958) have examined temperature and precipitation fluctuations in Arizona and New Mexico since the middle of the nineteenth century. Von Eschen found that a rising temperature trend in New Mexico has been dominant since approximately 1915, principally in the winter months, accompanied by a complementary decrease in total annual precipitation. Sellers also noted a definite downward trend in precipitation for Arizona and western New Mexico, beginning approximately in 1905 and continuing to the present. On the average, this decrease was about 1 in./30 yr, due almost entirely to a decrease in winter precipitation. Hastings and Turner (1965) suggest that such a trend may be the most important factor in the changing vegetation pattern of the Southwest, as noted from historical observations.

This marked trend toward less precipitation in the Southwest has been a major concern of water management agencies in recent years, in view of rapidly increasing demands for water supplies in the area as the population expands. Thomas (1959) points out the great problems involved in supplying the ever increasing demands for water in the area when recurrent drought periods of up to 30 yr in duration are a characteristic of the climate in the Southwest.

The only other studies of climatic fluctuations in the western United States have been climatic reconstructions, based on dendroclimatic techniques (Schulman 1938, 1956, Keen 1937, Fritts 1965, Fritts et al. 1971). Most of these studies, however, relate only to precipitation fluctuations and provide little information on temperature variations.

There are large and comparatively neglected resources of nineteenth century instrumental observations for the Western States that provide a more coherent and accurate picture of climatic fluctuations. As part of a continuing study for the Rocky Mountain area, this paper discusses early records for stations in southern Colorado. The work was undertaken to provide a climatic framework for the area of the San Juan Ecology Project (fig. 1), where winter cloud seeding operations are being conducted by the U.S. Bureau of Reclamation.

2. DATA AVAILABILITY

Climatic records for the western states (excluding coastal sites) were begun in the 1850-60 period by the U.S. Army, supplemented by individual observers under the direction of the Smithsonian Institution and the Patent Office, followed by the Signal Office in 1875. Regular Weather Bureau records began in 1896 (Landsberg 1960).

Useful data for southern Colorado are nonexistent

TABLE 1.—*Early climatic records in southwestern Colorado*

	Latitude	Longitude	Elev. (ft)	Precip. record begins	Precip. record ends	Temp. record begins	Temp. record ends	Observer category
1. Ames	37°54′	107°55′	8, 701	Nov. 1913		None		Weather Bureau
2. Cascade	37°40′	107°48′	8, 853	Sept. 1906	Dec. 1957	None		Weather Bureau
3. Durango	37°17′	107°53′	6, 550	Oct. 1894		Jan. 1896		Weather Bureau
4. Fort Garland	37°22′	105°23′	7, 937	Oct. 1858	Oct. 1883	Oct. 1858	Oct. 1883	U.S. Army Post
5. Fort Lewis	37°14′	108°03′	7, 595	Jan. 1881	Aug. 1891	Jan. 1880	Sept. 1890	U.S. Army Post
				Oct. 1911		Aug. 1917		Weather Bureau
6. Ft. Union, New Mexico	35°54′	104°57′	6, 880	Sept. 1851	Jan. 1919	Aug. 1851	Jan. 1919	U.S. Army Post & Weather Bureau
7. Hermosa	37°25′	107°50′	6, 633	Apr. 1875	Aug. 1882	May 1875	Aug. 1882	Voluntary Observer
8. Ignacio	37°08′	107°38′	6, 424	Jan. 1914		Feb. 1914		Weather Bureau
9. Montrose (No. 2)	38°29′	107°53′	5, 830	Jan. 1885		Jan. 1940		Weather Bureau
10. Silverton	37°48′	107°40′	9, 322	July 1906		July 1904		Weather Bureau
11. Telluride	37°57′	107°49′	8, 756	June 1911		June 1911		Weather Bureau
12. Trout Lake	37°50′	107°53′	9, 680	Oct. 1913	June 1958	None		Weather Bureau

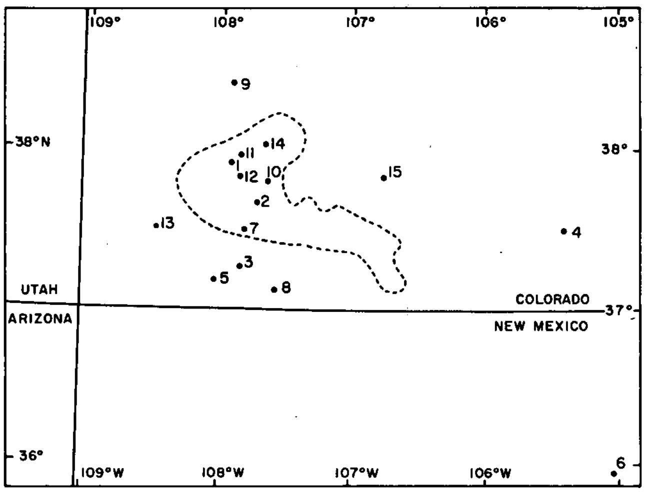

FIGURE 1.—Location of the following Colorado observing stations: (1) Ames, (2) Cascade, (3) Durango, (4) Fort Garland, (5) Fort Lewis, (6) Fort Union, N. Mex., (7) Hermosa, (8) Ignacio, (9) Montrose, (10) Silverton, (11) Telluride, (12) Trout Lake, (13) Dolores, (14) Ouray, (15) Wagon Wheel Gap. The dotted line delineates the San Juan Ecology Project area.

prior to 1850, and the two decades from 1850 to 1870 are virtually devoid of records. Earliest useful data sources in the area are from Fort Lewis, Fort Massachusetts, Fort Garland, Montrose, and Hermosa (fig. 1, table 1). The longest continuous sequence (25 yr) of nineteenth century climatic data in Colorado is from Fort Garland (1858–83).

In dealing with nineteenth century climatic data, one frequently encounters problems of interpretation. For example, standard observation times have changed over the last 120 yr (Roden 1966, table 2). In addition, the exact sites of the stations were often incompletely known and elevations given are frequently misleading. Thus, state historical and archaeological records have to be employed to fix the exact locations of many early recording sites.

Many techniques of testing data for homogeneity have been suggested (Mitchell 1961, Kohler 1949), but most tests rely on the availability of a number of station records against which the homogeneity of data from one station can be assessed. Hence, these procedures cannot be followed for the earliest stations. Moreover, such logic can become circular as the data against which a "key station" is tested may itself not be homogeneous and lead to erroneous conclusions. In addition, the regional testing of data in this way relies on the premise that stations over an area respond uniformly to synoptic scale events. In mountainous areas, where topographic effects are often important, severe constraints are placed on the standard tests of homogeneity. For the purposes of this study, therefore, the data are considered valid if approximately synchronous fluctuations are observed at two or more stations over the period in question. The very earliest data must inevitably be viewed with some caution.

3. ANALYSIS OF PRECIPITATION DATA

To investigate the spatial coherence of fluctuations in precipitation, we computed product moment correlation coefficients for a number of stations in and around the San Juan Ecology Project area. The period 1950–68 was chosen to provide maximum station density. In nearly all cases, interstation correlations, which averaged between 0.70 and 0.83, were significant at the 5-percent level and in many cases at the 0.1-percent level by Student's t test. This indicates that the San Juan area responds fairly uniformly as a region to seasonal variations in precipitation. Thus, key stations examined are likely to reflect characteristics similar to those of other stations in the area during the same time period, although such a relationship may not necessarily hold true over time (fig. 2). Correlations determined between Durango, Colo., and four stations (Fort Lewis, Ignacio, Silverton, and Telluride) for overlapping 25-yr periods (1914–38) to (1944–68) indicate a much lower correlation at the beginning of the record than during the most recent period. The spatial scale makes it unlikely that shifts in synoptic

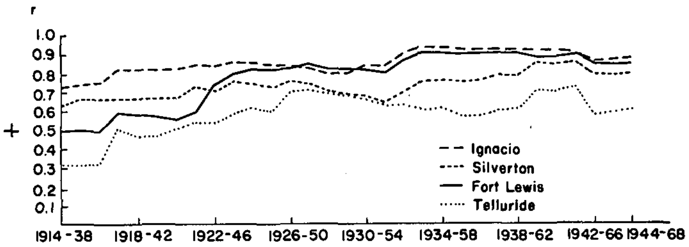

FIGURE 2.—Product moment correlations (with Durango) of annual precipitation for 25-yr overlapping periods 1914–38 to 1944–68.

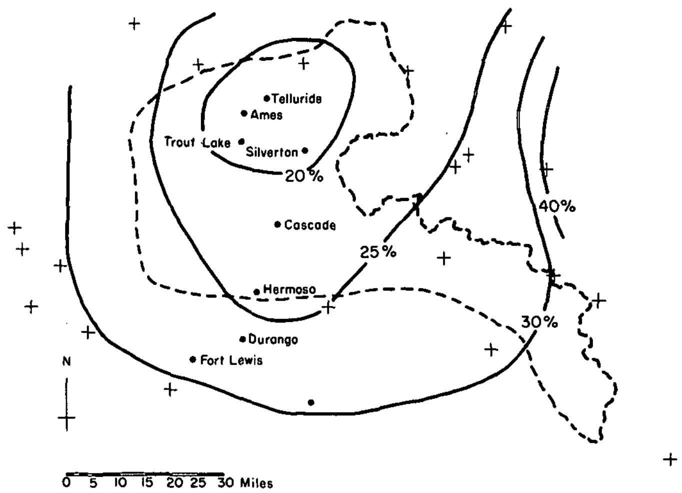

FIGURE 3.—Annual coefficient of variation for 1950–68 in southwestern Colorado. Dashed line delineates the San Juan Ecology area, crosses indicate location of stations used to map isolines, and key stations are named.

features could be responsible, and no obvious relationships were found between interstation correlations and distance to or elevation of adjacent stations. Similarly, no clear relationship exists between the correlation fields and regional patterns of precipitation variability. These changes in the level of correlation with time may simply be a result of the changes in quality of data with time, but further consideration of this question is desirable.

The variability of precipitation both annually and seasonally and its variation over time are of particular interest to the cloud seeding project. Coefficients of variation of annual precipitation were calculated for a large number of stations for the period 1950–68 and for a select number of stations for a longer period, 1914–68, according to the formula

$$C_{V_n}=\frac{s}{\bar{x}}\ (100\%)$$

where C_{V_n} is the coefficient of variation, s is the sample standard deviation, and $\bar{x}$ is the sample mean.

For 1950–68, the spatial pattern of the annual C_{V_n} (fig. 3) increases more or less radially from a core area embracing the San Juan County mountain massif and the stations of Telluride, Ames, and Silverton, Colo. The values range from 17.6 percent at Ames to 43.6 percent at Wagon Wheel Gap. Winter variability showed a smaller range in values from 21.1 percent at Ouray to 37.3 percent at Dolores. Again, variability decreased away from the San Juan County massif. The generally lower winter values reflect the cyclonic origin of winter precipitation.

Seasonal coefficients of variation for selected stations between 1914 and 1968 are given in the upper half of table 2. For all stations except Durango, winter (November to March) exhibits the lowest variability of precipitation. If the stations are examined on the basis of elevation, an interesting grouping is apparent (table 2, lower half). For stations over approximately 9,000 ft (2743 m), spring precipitation (April, May) shows less variability than at stations between 8,000 and 9,000 ft (2437 and 2743 m), and much less than at stations below 8,000 ft (2438 m). This presumably reflects the persistence of winter conditions into these months at higher elevations. For most stations, the highest variability of precipitation occurs in the transitional seasons, spring and fall.

Precipitation variability, like total precipitation amounts, is clearly subject to change with time (fig. 4, table 3). In general, variability is seen to have declined in the most recent period, particularly in the winter months, and this may partly account for the changing correlation fields over time, already noted.

TABLE 2.—*Seasonal and annual values of the coefficient of variation* (C_{V_n}) *of precipitation (1914–68)*

	Elevation (ft)	Spring	Summer	Fall	Winter	Annual
1. Ames	8,701	39.3	32.0	55.4	27.8	20.8
2. Cascade*	8,853	54.8	43.7	62.3	34.0	28.5
3. Durango	6,550	65.6	37.1	60.2	39.1	26.1
4. Fort Lewis	7,595	53.0	39.5	57.3	35.1	27.3
5. Ignacio	6,424	68.0	67.2	56.5	35.5	27.9
6. Rico	8,842	44.5	37.2	59.1	23.2	22.5
7. Silverton	9,322	35.5	36.0	51.7	34.4	22.3
8. Telluride	8,756	43.8	42.7	56.2	35.9	27.2
9. Trout Lake*	9,680	37.8	45.0	57.7	30.1	23.6

*1914–57

	Stations	Elevation (ft)	Increasing Coefficient of Variation
I	Trout Lake	9,680	Winter→Spring→Summer→Fall
	Silverton	9,322	Winter→Spring→Summer→Fall
	Cascade	8,853	Winter→Summer→Spring→Fall
	Rico	8,842	Winter→Summer→Spring→Fall
II	Telluride	8,756	Winter→Summer→Spring→Fall
	Ames	8,701	Winter→Summer→Spring→Fall
	Fort Lewis	7,595	Winter→Summer→Fall→Spring
III	Durango	6,550	(Summer→Winter)→Fall→Spring
	Ignacio	6,424	Winter→Summer→Fall→Spring

Changes in the coefficient of variation for summer precipitation do not show the spatial coherence of the winter seasons. Some stations show very large decreases in variability; others, increases. In view of the more convective type of storm activity in the summer months, this result is not surprising. Neither season shows any clear spatial pattern of change in variability.

Precipitation-elevation relationships for the period 1961–70 indicate a regression relationship (r=0.76, 0.1-

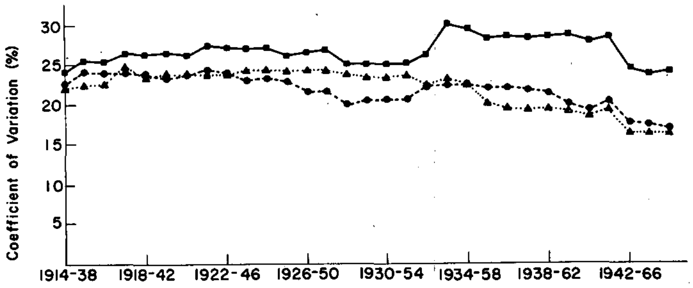

FIGURE 4.—Annual coefficients of variation for 25-yr overlapping periods, 1914–38 to 1944–68 for Durango (squares), Ames (triangles), and Silverton (circles).

percent significance level) in which mean annual precipitation increases approximately 2.5 cm for each 100 m increase in elevation (approximately 3 in./1,000 ft). Stations east of the Continental Divide do not show a close relationship to those west of the Divide and are, hence, not considered in the regression analysis. An interesting change in the precipitation-elevation relationship is apparent when two periods of data for the same set of stations are examined (fig. 5). For twelve stations in the San Juan Mountains, precipitation increased 4.1 cm/100 m (4.87 in./1,000 ft) for the period 1940–49 and only 2.6 cm/100 m (3.15 in./1,000 ft) for the period 1950–60. This change in the relationship was due principally to the mean annual precipitation at higher elevations decreasing more between the two periods than at stations at lower elevations. Williams and Peck (1962) noted a similar phenomenon in the mountains of north central Utah; on days with cold Lows, precipitation was heavier at lower elevations than at higher elevations. Thus, the change in the precipitation-elevation relationship in southwestern Colorado may be related to a change in the frequency of cold Lows affecting the area.

Annual and seasonal precipitation amounts at nine Weather Bureau stations were smoothed by a 9-yr weighted binomial running mean. The stations chosen all have records going back to 1914 or earlier, and Durango has a good record back to 1896. Nineteenth century data analysis is discussed below.

Winter (November–March), spring (April, May), summer (June–August) and fall (September, October) values were computed. The following station records were examined: Ames, Cascade, Durango, Fort Lewis, Ignacio, Silverton, Telluride, and Trout Lake; two of the stations, Durango and Silverton, have been chosen as representing most of the characteristic features (figs. 6, 7). As one might expect, the station records are not identical; but, by classifying the peaks and troughs for each station as major or minor, the following features are clear for each season (years mentioned are the midpoint of a 9-yr period):

1. Winter is characterized by large fluctuations, although their magnitude varies from station to station. A major low precipitation value occurred around the turn of the century followed by a rapid increase to a peak value in 1908. In the case of Durango, this peak was over 200 percent of the 1900–01 low value. Precipitation then decreased to a minor low around 1916 followed by an increase to another peak in 1919–22. This minor peak was followed by a drastic fall in precipitation over the next decade to a minimum value for the period at approximately 1929–32. An equally dramatic rise followed, resulting in a peak generally around 1936–38. In the case of Telluride, precipitation rose from a mean of 15.7 cm (6.17 in.) in 1930 to a mean of 35.1 cm (13.83 in.) in 1938. Minor minima then occurred in 1945–46 and 1961–62 with intermediate peaks around 1948–51 and 1956–57.

In some cases, such as Ames, Ignacio, and Silverton, Colo., a definite downward trend is obvious throughout the record, whereas, in other cases (Rico and Fort Lewis),

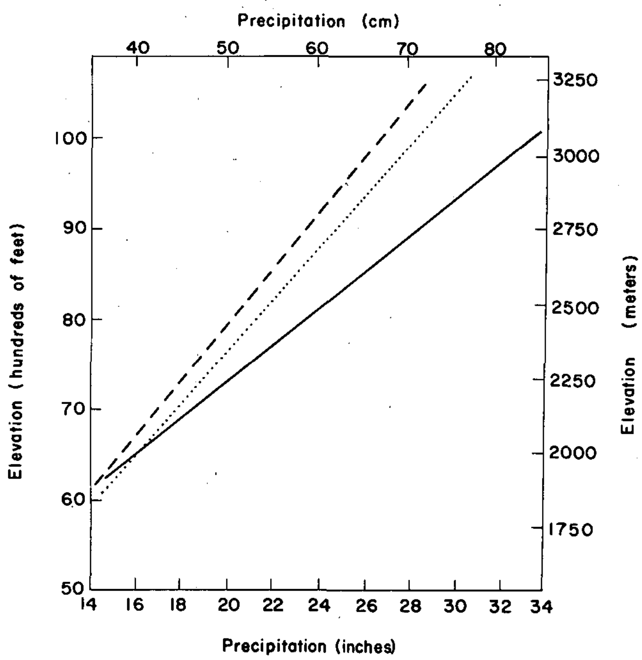

FIGURE 5.—Dependence of mean annual precipitation on elevation during 1940–49 (solid line), 1950–60 (dashed line), and 1961–70 (dotted line). All stations are in the San Juan area of southern Colorado, west of the Continental Divide.

TABLE 3.—*Annual coefficients of variation (1914–40) and (1941–68)*

	Period I	Period II	Period II minus Period I
Winter			
Ames	30. 1	25. 9	−4. 2
Durango	45. 0	31. 5	−13. 5
Fort Lewis	40. 7	27. 8	−12. 9
Ignacio	36. 4	33. 1	−3. 3
Rico	25. 1	21. 2	−3. 9
Silverton	35. 2	30. 8	−4. 4
Telluride	47. 3	27. 7	−19. 6
Summer			
Ames	35. 3	28. 3	−7. 0
Durango	33. 3	41. 2	+7. 9
Fort Lewis	40. 8	37. 4	−3. 4
Ignacio	44. 5	47. 6	+3. 1
Rico	36. 2	38. 5	+2. 3
Silverton	42. 3	27. 3	−15. 0
Telluride	47. 9	37. 8	−10. 1

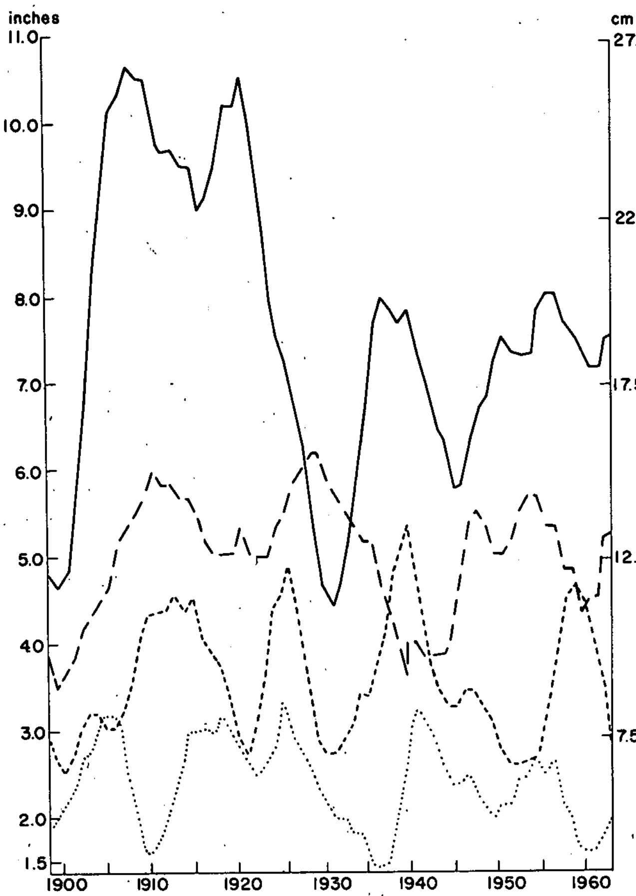

Figure 6.—Nine-year weighted binomial running means of precipitation at Durango (1895–1968) for spring (dotted line), fall (small dashed line), summer (large dashed line), and winter (solid line).

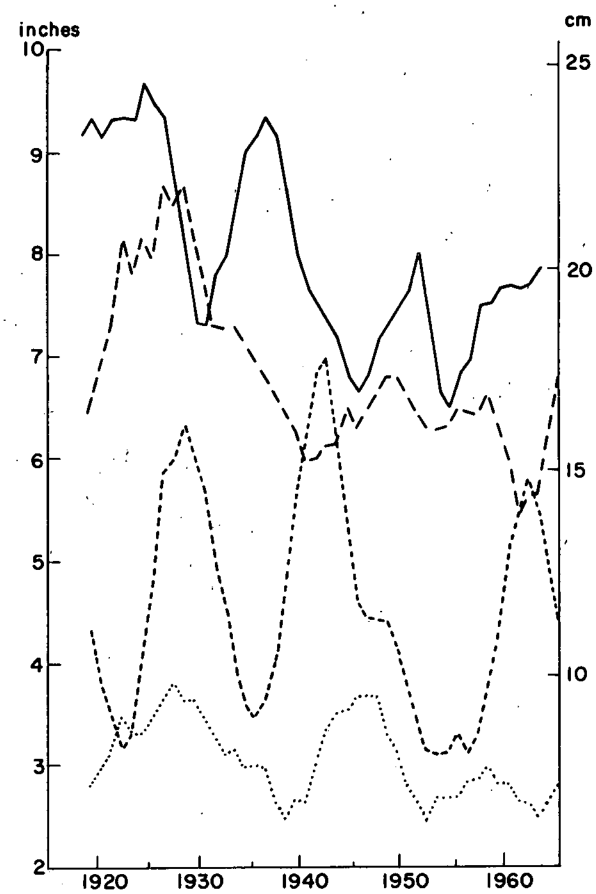

Figure 7.—Same as figure 6 for Silverton (1914–68).

the record only trends downward after the 1936–38 high point. A number of records show no distinct trend.

In short, the winter season record is one of large fluctuations with peaks in the record at intervals of approximately 12–15 yr. Minima do not exhibit such a regular pattern of occurrence. No trend is common to all stations, but a number show a definite downward trend.

2. Spring fluctuations in precipitation are small with major troughs at the turn of the century, around 1910–11, 1936–37, and 1961–63. Minor troughs occur around 1923 and 1951–52. Major peaks occur around 1905–07 and 1941–42 and minor peaks around 1919–20, 1926, and 1955–57. The major peaks are also characteristic of other seasons with the exception of the 1910–11 trough, which is unique to spring season. Silverton, Ignacio, and Durango show a slightly falling trend after 1926, but this is not recognizable in the other records.

3. During summer, a number of stations (in particular, Rico, Silverton, Ignacio, Fort Lewis, and Trout Lake) show a marked downtrend in the record. Major troughs occur at 1900, 1922–24, 1940–42, 1950–52, and 1960–62. At some stations, the 1950–52 trough should perhaps be termed minor. Major peaks are around 1927–29 and 1947–48. Some stations show minor peaks at approximately 1936–38 and 1954–55. The peaks in the records thus suggest an 8- to 10-yr cycle. Some stations indicate a major peak at approximately 1910–12, and, if the 1936–38 peak is considered to be only a minor variation, an interval for both peaks and troughs of approximately 18–20 yr is apparent with the peaks 6–8 yr after major troughs.

4. Fall exhibits fluctuations of high frequency. Major troughs occur at the turn of the century, 1921–22, 1933-34, and 1951-55. Major peaks occur at approximately 1927, 1941, and 1960–61. During the period 1938–46, the precipitation at Cascade in the fall was 350 percent of that received in the same season during the 1930–38 period.

Nineteenth century data were taken from Greely (1891) and checked against the original monthly records (available from the National Archives in Washington, D.C.) when figures appeared unreliable. For example, precipitation figures for 1870–72 at Fort Garland seemed unrealistically large. Comparison with the original records showed that the data for these years were entered in cubic centimeters instead of inches, as assumed by Greely. Cross-checking different data sources in this way helped to eliminate possible errors in the nineteenth century data used.

Although few stations were operative in southern Colorado prior to the establishment of the U.S. Weather Bureau, a number of generalizations can be made. Annual precipitation totals appear to have fallen from the late

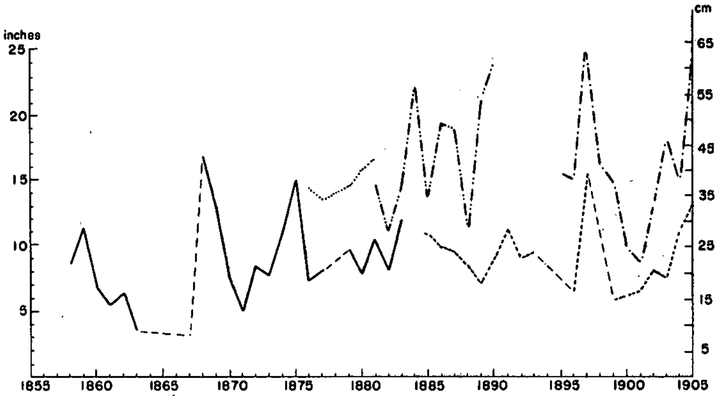

FIGURE 8.—Nineteenth century records of annual precipitation (1858–1905) for Fort Garland (solid line), Hermosa (dotted line), Montrose (small dashed line), Fort Lewis (two dots and dashed line), and Durango (one dot and dashed line).

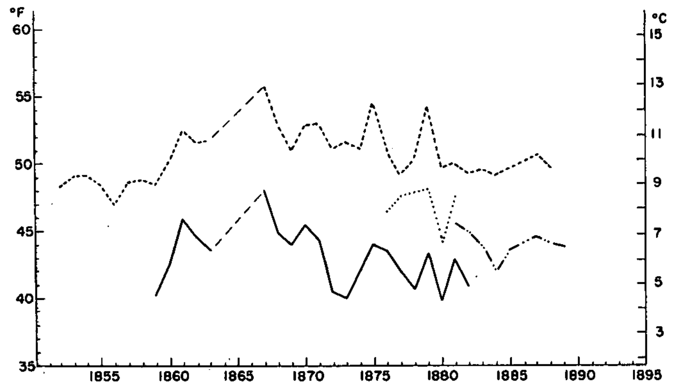

FIGURE 9.—Nineteenth century records of mean annual temperatures (1852–99) for Fort Garland (solid line), Hermosa (dotted line), Fort Union, N. Mex. (small dashed line), and Fort Lewis (two dots and dashed line).

1850s to the early 1860s and then to have risen steadily from about 1870 to approximately 1890 (fig. 8). For the subsequent 5 yr, data are scarce, and the next reliable feature is the marked trough at approximately 1900–01, which has already been discussed.

Mean annual precipitation at Fort Garland for 1858–74 was 20.9 cm (8.21 in.). The nearest station operative today is Blanca, where the 1931–60 normal was 20.1 cm (7.92 in.). The elevation of Blanca, however, is 7,500 ft (2286 m) compared to 7,937 ft (2419 m) at Fort Garland. Using an average increase of 3.0 cm/100 m (3.64 in./1,000 ft), we would have expected precipitation at the Fort Garland site to have been approximately 1.6 in. more than at Blanca. However, the annual values for 1858–74 indicate only slightly more precipitation than current normals at Blanca, thus suggesting that conditions were at least as dry in the 1860s as in the 1931–60 period.

When seasonal fluctuations are examined, the records indicate that the largest seasonal increases in precipitation occurred during winter and summer months. At Fort Garland, for example, the mean winter precipitation for 1858–68 (6 yr, due to missing data) was 2.7 cm (1.08 in.); for 1873–82 (10 yr), it was 6.9 cm (2.7 in.).

4. ANALYSIS OF TEMPERATURE DATA

Long-term temperature records for southern Colorado are less common than long-term precipitation records. Virtually no records for the area are available for the period 1889–1900. For this reason, nineteenth century stations operative in adjacent states were examined to supplement the data available in Colorado; one such record (Fort Union, N. Mex.) is shown in fig. 9.

Temperatures rose markedly during the late 1850s and 1860s to a high around 1867. Temperatures then fell slowly until 1890 and possibly over the subsequent 10 yr (here the record is absent), with a continuing decline until approximately 1930. Again, seasonal values shed more light on the fluctuations. Cooling during 1870–1930 is most marked in the spring, fall, and winter seasons at all stations, suggesting that the average length of the growing season in the late 1920s was considerably shorter than in the early 1870s.

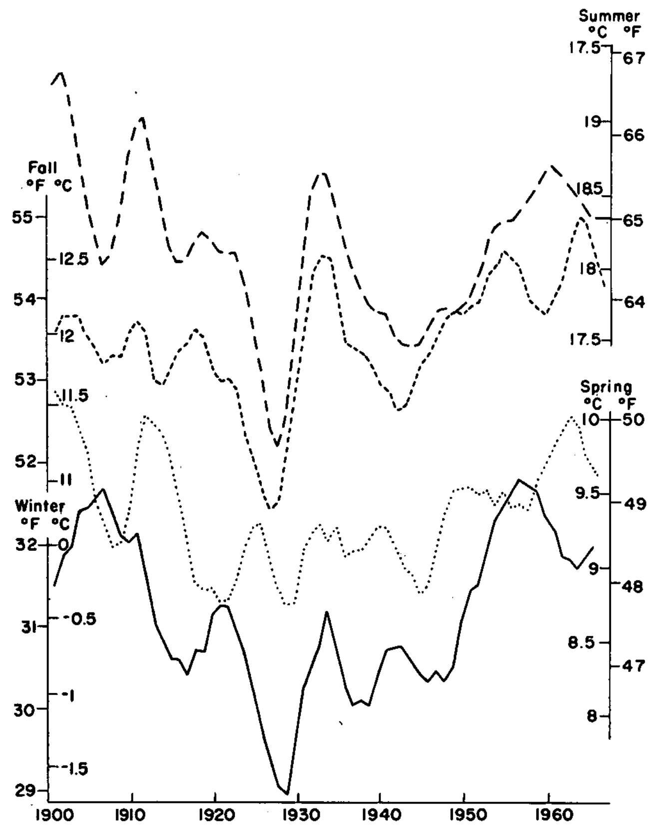

FIGURE 10.—Nine-year seasonal mean weighted binomial running mean temperatures at Durango (1897–1968) for spring (dotted line), fall (small dashed line), summer (large dashed line), and winter (solid line).

Although the data are sparse prior to 1900, a comparison of the general trend of temperature and precipitation for 1850–90 shows an expected inverse relationship, suggesting that the trends discussed are fairly reliable. Precipitation totals during the late 1850s and early 1860s fell while mean temperatures rose (particularly during the winter season). From the late 1860s to approximately 1890, the reverse is true, a cooling trend being paralleled by increasing precipitation. This is further illustrated by the record at Silverton for the period 1925–65. At this station, precipitation shows a mean decrease of 3.8 mm/yr, whereas the temperature record shows a mean warming of approximately 0.017°C/yr.

After 1930, most stations show a reversal of the cooling trend, and, at Durango, winter temperatures were at a similar level about 1905 and 1956–58 (fig 10), almost 2.2°C higher than the 1930 minimum. The transitional seasons of spring and fall, in general, show warming trends from the 1930 low or earlier, to the early sixties. This trend is also seen in some summer records although the magnitude of the warming trend is not as great. For example, Silverton shows a mean warming since 1910 of approximately 2.2°C during the fall season, 1.7°C in the spring, and 0.8°C in the summer; in winter, the increase is less than 0.5°C for the entire record. There is evidence of an apparent cooling during the late 1960s during the fall, spring, and summer months, but this does not appear in all the winter season records. However, such a reversal of the main trend may only be a short-term fluctuation within the long-term upward trend apparent over the previous 30 yr.

5. CONCLUDING REMARKS

Examination of the seasonal precipitation changes shows that minima were well marked around 1860 (based on annual totals), 1900 (in all four seasons), and 1930–35 (except in summer). Minima affecting summer and fall occurred around 1922 and 1950–55 and one affecting winter and spring around 1962. The pattern fits broadly into that noted by Thomas (1959) for this area and the Pacific border areas. October–March precipitation, as a percentage of annual total, was 38 percent for 1925–35 at Durango compared with 50 percent for 1895–1968. Winter precipitation was also reduced, although less markedly, around 1900 and between 1946–55.

The evidence of a wetter, warmer period in this area during the 1850s and 1860s compared with the 1931–60 normals (Wahl and Lawson 1970) is at variance with our finding of warmer conditions at least as dry as at present. This probably reflects our more local scale of analysis, but it suggests the need for caution in applying broad-scale studies based on few stations to specific areas, particularly in the mountainous parts of the country. We have not attempted specific evaluation of departures from the current normals in view of the limited duration of station records. Bearing in mind the heterogeneous nature of the sites involved, one cannot compare records for the earliest stations and the present ones, especially in view of the evidence of changes in the spatial coherence of the climatic patterns over time.

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